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WORKSHOP ON
**PAST AND PRESENT SOLAR
RADIATION:**
**The Record in Meteoritic and Lunar
Regolith Material**



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WORKSHOP ON

PAST AND PRESENT SOLAR RADIATION:
The Record in Meteoritic and Lunar Regolith Material

Compiled by
R. O. Pepin
and
D. S. McKay

A Lunar and Planetary Institute Workshop
Mainz, Germany
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Cover: Photographed from Skylab in June, 1973. Coronagraph (sun's disk artificially eclipsed). The moon is moving into a position between the earth and sun, producing the total eclipse of June 30, 1973.

Courtesy of High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colorado.

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Introduction

The surfaces of airless bodies in the solar system are directly exposed to ions streaming outward from the sun. These solar particles embed themselves in the dusty regoliths of rock fragments, mineral grains, and impact glasses, accumulated from billions of years of rock erosion by meteorite bombardment, that now lie meters or more deep on the surfaces of the moon and the asteroidal parent bodies of meteorites. Therefore each irradiated regolith grain may hold a small slice of the history of the sun, as it was when the solar wind and solar flare tracks and particles now trapped within it were implanted.

✓ The exciting potential of regolith materials as records of solar particle emission through time was realized even before the Apollo missions, when the large abundances of noble gases in the dark portions of the light-dark structured gas-rich meteorites were recognized as trapped solar wind. These brecciated meteorites, cemented by impact on asteroid regoliths, provided the first measurements of the chemical and isotopic composition and the energy of the ancient wind. But it was the lunar soil samples from Apollo, together with the light noble gas composition of the contemporary solar wind measured directly by the Apollo Solar Wind Composition experiments, that provided the major impetus for detailed study of regolith grains as fossil detectors of solar history by a broad community of planetary and solar geoscientists and solid-state physicists. Here, too, the intrinsic complexities of the detectors and of the records they carry became obvious. Regoliths are dynamic systems. Individual grains move vertically and laterally as the regolith is churned and overturned on various time scales by meteoritic impact. Fragments spalled from larger rocks are comminuted to smaller and smaller sizes, wholly or totally melted and welded into glassy agglutinates, and again eroded as soils evolve toward "mature" equilibrium between production and destruction of its component grains. Ejecta from major impact may deeply bury a given soil, interrupting its episodic cycles of exposure to the sun at the surface by long periods of quiescent residence—perhaps for billions of years—deep in the regolith. The chronological record of exposure is thus badly scrambled: there is no measurement that reveals *per se* when in the past a particular grain acquired its record of solar particles and tracks. And the detector grains themselves are imperfect in their intrinsic abilities to register radiation damage tracks, or to retain these tracks and preserve implanted particles from diffusive redistribution and loss in the thermal environments created in the upper regolith by solar insolation and high temperature micrometeorite impacts.

It is clear that natural dust grains on planetary surfaces are by no means ideal recorders of their radiation environments through time, and that the general problem of interpreting the records of solar particle emission in all the diverse components of lunar and meteoritic regolith samples is a formidable one. A profitable line of attack, in the area of solar wind and flare particles in particular, has focused on the search for materials that are structurally most retentive for implanted ions, and have escaped excessive comminution or the very high temperatures of agglutination processes. Pure large mineral grains satisfy the second criterion, and, among the relatively common lunar minerals, ilmenites and some of the pyroxenes and olivines can retain implanted gases as light as neon. Gas redistribution and loss effects overprinted on regolith records in the lunar thermal environment are not as pronounced in meteorite regolith breccias, where diffusive fractionation of the primary solar wind composition is less severe and agglutinates are rare. For this reason, and because asteroidal regolith grains preserved in gas-rich meteorites contain generally older (probably prior to 4 b.y.) records of solar particle history, more attention is swinging to these samples despite their scarcity and their significantly lower loading of solar tracks and particles compared to the heavily irradiated lunar soils.

↘ Study of natural extraterrestrial detectors for clues to the history of particle emission from the sun began with the gas-rich meteorites in the 1960s and now, after two decades of lunar and meteorite research, is an established and significant component of the present broad and interdisciplinary effort to formulate and answer the central questions of solar system evolution. Data and interpretations from this study are obviously relevant to the composition and physical acceleration mechanisms in the solar source regions

for flares and the solar wind and their variations with time. Yet, historically, there had been little communication between the geoscience and solar physics communities, at least in this area, until the convening of the LPI Topical Conference on the Ancient Sun: Fossil Record in the Earth, Moon, and Meteorites at the National Center for Atmospheric Research in March of 1979. The Proceedings* of this conference represent a relatively comprehensive status report of progress in the study of natural detectors as of five years ago, as well as a first attempt to collect the perceptions of both communities into one volume.

Several developments since 1979 point to the scientific potential of a new and focused research concentration on natural solar detectors. The LPI Workshop described in this report was one element in the organization of a new effort to encourage discussion and investigation of this aspect of solar history studies, and, more generally, to promote research involving a full range of outstanding questions about lunar and asteroidal regoliths. Presentations to the workshop, summarized below with reference to the abstracts included in this volume, touched on many of these questions.

During the past five years, the Zürich group has played a leading role in directing attention to the records in lunar regolith mineral grains. Many of the implications of their data for regolith dynamics and for the history of solar corpuscular radiation were reviewed by Etique *et al.*, Signer *et al.*, and Wieler *et al.* In an extension of the Zürich work by a somewhat different experimental technique, Frick *et al.* found evidence in lunar ilmenites for two solar gas reservoirs, one a virtually pristine surficial record of the elemental and isotopic compositions of irradiating solar wind ions, superimposed on another reservoir apparently populated by earlier irradiations and subsequently altered by diffusion. In a related study, Becker *et al.* found that essentially unaltered records of very early solar ion emissions have apparently been retained in iron grains from gas-rich meteoritic regolith breccias. The fundamental and difficult problem of determining the actual time and duration of exposure of detector grains to solar radiation, which must eventually be solved if possible secular compositional changes are ever to be ordered in a chronologically quantitative way, was elegantly addressed by Eugster in a pair of talks.

An equally important question is that of the actual radial distributions of trapped solar ions now surviving in irradiated detector grains, since they bear so directly on initial implantation profiles and the extent to which these, and the associated elemental and isotopic compositions of the trapped gaseous species, may have been altered by diffusional migration and loss during and following irradiation. Assessment of these distributions by the etching and step-wise oxidation techniques used by the Zürich and Minneapolis groups is in many respects crude and inferential. Kiko and Kirsten's report on direct measurement of concentration profiles by the unique Heidelberg Gas Ion Probe illustrates the general kind of experimental approach that must be pursued in future studies of solar-derived volatile elements in regolith grains. Detection and measurement of solar refractory elements in these materials is a formidable experimental challenge. Techniques much more sophisticated than simple gas removal are required, and are applicable only to restricted situations where the implanted solar component is not overwhelmed by the natural abundances of these elements in the grain minerals. As pointed out by Manuel in his discussion of the importance of data on solar refractory element compositions, many of these data will probably have to come from direct measurement of present-day solar wind and flare particles in space.

One direct measurement of this kind, by spacecraft instruments, of a neon isotopic composition in solar flares that is very different from that in the solar wind, has raised the interesting possibility of unsuspected physical fractionation mechanisms that may be operative in one or the other of the flare and wind source regions. This has catalyzed an effort by two groups, discussed here by Nautiyal and Rao and by Wieler *et al.*, to read the solar flare neon record in lunar (and, eventually, in meteoritic) regolith grains. Another investigation involving flare irradiation relates to a very early epoch in solar history. New astronomical observations indicate high X-ray, ultraviolet, and particle emission activity in young solar-type stars during their first half-billion years of evolution. This phase probably overlaps accessible regolith records contained

**The Ancient Sun: Fossil Record in the Earth, Moon, and Meteorites* (edited by R. O. Pepin, J. A. Eddy, and R. B. Merrill), *Geochim. Cosmochim. Acta Suppl.* 13, 581 pp., Pergamon Press, New York, 1979.

in gas-rich meteorites and old lunar breccias. Its most likely signatures from our sun would be a marked increase in track densities and in spallation gas abundances produced by solar energetic particles, relative to an assumed constant production by galactic cosmic rays. Hohenberg *et al.* reported that some individual grains from gas-rich meteorites do indeed appear to display just this signature. Confirmation of high early solar activity is crucial for modeling the evolution of planetary atmospheres because of the sensitivity of the evolutionary track to ultraviolet radiation density. Deducing the actual flux and energy spectrum of energetic solar particles in ancient epochs of solar history from available records will be an extraordinarily difficult task, principally because of profound uncertainties in duration of exposure. On the other end of geologic time, a reasonable estimate can be made of absolute fluxes averaged over time periods up to the past ten million years or so from radionuclide measurements in lunar surface samples, as summarized by Arnold *et al.*

This workshop was developed in parallel with formation of a new LAPST (Lunar and Planetary Sample Team) initiative to highlight the study of lunar regolith breccias. Two presentations, by McKay and Wentworth and by Blanford, made it very clear that these regolith breccias are key samples for tracking the evolution of solar particle emission. They have the inherent chronological advantage of closure: at various times in the past, their formation by impact from regolith soils shielded their interior grains from further solar irradiation, and the solar particles and tracks now present in these grains thus represent an earlier epoch of solar history than those in most unconsolidated soils. Some of the most ancient known samples of solar wind are trapped in Apollo 11 and 17 breccias that were apparently assembled billions of years ago. These are the materials that contain the extraordinarily light nitrogen, discussed during the workshop by Kerridge and by Norris *et al.*, that has raised fundamental questions about secular solar wind variations and the components of nitrogen present in the primitive solar system. Equally important are the meteoritic regolith breccias. The most gas-rich member of this group, the H-chondrite Fayetteville that has hitherto been unavailable for large-scale systematic investigation, is now the subject of a comprehensive consortium study headed by Derek Sears of the University of Arkansas. Preliminary plans established at an organizational meeting of the consortium, held in conjunction with the 15th Lunar and Planetary Science Conference in March 1984, call for slabbing of the main Fayetteville mass at the JSC sample processing and curatorial facility in Houston, followed by petrographic examination, controlled sampling, and distribution for detailed study.

It can fairly be said that the combination of recent discoveries, new directions to be explored, unique samples, maturing experimental techniques, and the widespread community commitment reflected in the number of workshop attendees and their vigorous and far-ranging discussions, demonstrates the continued vitality and potential of this area of solar and planetary research.

David S. McKay
Houston

Robert O. Pepin
Minneapolis

Program

The two-day workshop was held at the Max-Planck-Institut für Chemie, Mainz, FRG, on September 3-4, 1983, just prior to the 46th Meteoritical Society Meeting. The convenors and participants wish to thank the workshop hosts, Professor H. Wänke and Professor F. Begemann of M-P-I, for their generous and efficient support of the meeting.

Saturday, September 3, a.m.

Topic I

Solar Particle History: 1983 Version

J. R. Arnold, R. C. Reedy, and K. Nishiizumi

Particle Track Measurements in Lunar Regolith Breccias

George E. Blanford

SCR and GCR Exposure Ages of Plagioclase Grains from Lunar Soil 61501

Ph. Etique, H. Baur, P. Signer, and R. Wieler

Studies of Light Noble Gases in Mineral Grains from Lunar Soils; A Status Report

R. Wieler, Ph. Etique, and P. Signer

Distribution of Solar Wind Implanted Noble Gases in Lunar Samples

J. Kiko and T. Kirsten

Solar Wind Helium, Neon, and Argon Released by Oxidation of Metal Grains from the Weston Chondrite

R. H. Becker, R. S. Rajan, and E. R. Rambaldi

Saturday, September 3, p.m.

Topic II

Petrographic Survey of Lunar Regolith Breccias

D. S. McKay and Sue Wentworth

Topic III

The Dating of Pre-Exposure Times of Lunar Rocks and Soils

O. Eugster

**Saturday, September 3, p.m. and
Sunday, September 4, a.m.**

Topic IV

Solar Flare Neon and Solar Cosmic Ray Fluxes in the Past Using Gas-Rich Meteorites

C. M. Nautiyal and M. N. Rao

Boundary Conditions on the Early Sun from Ancient Cosmogenic Neon in Meteorites

C. M. Hohenberg, M. W. Caffee, T. D. Swindle, and J. N. Goswami

The Composition of Noble Gases Trapped 2.5 AE and 3.6 AE ago

O. Eugster

The Need for Isotopic Data on Refractory Elements in the Solar Wind

O. K. Manuel

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Lunar Nitrogen—Secular Variation or Mixing?

S. J. Norris, I. P. Wright, and C. T. Pillinger

The Reality of the Secular Change in Solar Wind Nitrogen Isotopes

J. F. Kerridge

Release of Noble Gases and Nitrogen from Grain-Surface Sites in Lunar Ilmenite by Closed-System Oxidation

U. Frick, R. H. Becker, and R. O. Pepin

Nitrogen and Noble Gases in the 71501 Bulk Soil and Ilmenite as Records of the Solar Wind Exposure: Which is Correct?

P. Signer, H. Baur, Ph. Etique, and R. Wieler

Sunday, September 4, p.m.

Topics V and VI

General Discussion

Workshop Rationale

The principal question addressed in the workshop was the extent to which asteroidal and lunar regoliths have collected and preserved, in meteoritic regolith breccias and in lunar soils and regolith breccias, a record of the flux, energy, and compositional history of the solar wind and solar flares. Six central discussion topics were identified in the call for contributions, along with a number of subtopics.

Topic I: Trapped solar wind and flare gases, tracks, and micrometeorite pits in regolith components

- Contemporary solar fluxes and energy spectra
- Concentrations and radial distributions within grains
- Theoretical and measured implantation profiles
- Dynamical models of exposure, burial, re-exposure, and destruction by fragmentation and agglutination as a function of grain size

Topic II: Comparison between lunar regolith breccias, meteoritic regolith breccias, and the lunar soil

- Comparative maturity of "old" lunar regolith breccias and typical lunar soils
- Relation of maturity indices such as trapped solar gases and agglutinate contents in "old" and "young" lunar breccias and soils
- Are "old" lunar breccias deficient in some petrologic components compared to soils?
- Do "old" lunar breccias contain different ratios of siderophile elements from micrometeorites, compared to "young" breccias and soils?
- Why do meteoritic regolith breccias contain few if any agglutinates?
- Comparative solar wind loading in meteoritic and lunar breccias

Topic III: The special role of regolith breccias and the challenge of dating their times of compaction

- The general time-base problem: when and for how long was a particular regolith component exposed to solar particle radiation?
- Classes of samples (crater ejecta, cores, breccias) whose irradiation epochs or closure times are determinable, at least in principle

Topic IV: Implications of the data for the flux and compositional history of solar particle emission, composition and physical mechanisms in the solar source regions, and the composition of the early nebula

- Secular variations in the isotopic composition of solar wind nitrogen and other elements
- Variations in the elemental composition and flux of the solar wind
- The isotopic composition of solar flare neon
- Astronomical evidence for enhanced activity and particle emission in the early sun, and the search for its signature in ancient regolith materials

Topic V: How and to what extent have records of incident radiation been altered in various types of grains?

- Mineral grains as "least-altered" detectors
- Diffusion, annealing, and other physical effects that fractionate or otherwise perturb records of the primary flux during or following irradiation
- What happens to implanted solar gases during formation of constructional particles (agglutinates and microbreccias)?
- What are the "best" natural detector materials for preservation of various kinds of radiation records?

Topic VI: Direction and organization of future research

- Identification of critical meteoritic and lunar samples for study
- Separation of soil and breccia samples into individual mineralogic and/or grain-sized components
- Essential data: petrology, grain chemistry, noble gases, carbon, nitrogen, tracks, other
- Experimental techniques
- Organization of consortia
- The LAPST lunar regolith breccia initiative
- Future workshops, meetings, newsletters, and publications

Topic I is the present data base and how it might have been acquired by detector grains that are components of dynamic regoliths; Topic II is concerned with the interrelationships among different sample types and what they might reveal about processes; Topic III concerns the time coordinate: when were primary irradiation signatures recorded in regolith materials?; Topic IV asks what we think we have discovered from regolith studies about the characteristics and history of solar particle emission; Topic V focuses on the question of how well the data actually represent the primary radiations; and Topic VI is an attempt to assess what should be done, and how, for maximum scientific return in this study area in the future.

ABSTRACTS

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SOLAR PARTICLE HISTORY: 1983 VERSION.

J. R. Arnold, R. C. Reedy* and K. Nishiizumi, Dept. of Chemistry, Univ. of Calif., San Diego, La Jolla, CA 92093; *Los Alamos National Lab., Los Alamos, NM 87545.

It has long been known that the great majority of nuclear-active solar particles are emitted in a few large storms in each 11-year cycle. A single storm (or group of storms) in August 1972 dominated the fluence of particles of energy >10 MeV. Such storms can occur, it seems, at any time within the more active half of the cycle.

On a time scale long compared to 11 years, our knowledge comes from two sources. Terrestrial ^{14}C sets limits on the largest proton bursts that can have taken place in the last 8000 years. Lunar surface samples have yielded data on mean fluxes on a time scale from the ^{14}C to the ^{53}Mn mean life. Our group has found a mean flux of 70 protons >10 MeV and a rigidity constant $R_0 = 100$ MV to be robust on the 10^6 - 10^7 year time scale [Kohl, et al., 1978]. Over the shorter periods represented by ^{14}C and ^{81}Kr the fluxes seem to have been higher [Boeckl, 1972; Yaniv, et al., 1980], by a factor of roughly three. This is discussed in detail by Reedy, Arnold, and Lal [1983a, b].

The advent of accelerator mass spectrometry creates new opportunities in this field of study as elsewhere. The higher sensitivity of the method permitting drastic reduction of sample size, is obvious to all. The improved precision already demonstrated [Nishiizumi, et al., 1983], with further gains to be expected, may prove equally significant. Some examples will be discussed.

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SOLAR WIND HELIUM, NEON AND ARGON RELEASED BY OXIDATION OF METAL GRAINS FROM THE WESTON CHONDRITE. R. H. Becker¹, R. S. Rajan² and E. R. Rambaldi²,
¹School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455;
²Space Science Div., 183-501, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109.

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^{were carried out}
~~We have carried out~~ a set of experiments to test the feasibility of determining unfractionated elemental and isotopic ratios for the noble gases in the presumably ancient solar wind present in the gas-rich meteorites. The difficulty with most previous measurements on solar wind noble gases, including much of the work on lunar materials, is that they have been done on silicates, which are susceptible to diffusive gas losses. ~~We have attempted to avoid the problems of diffusive loss by analyzing metal rather than silicates.~~ It has previously been demonstrated that noble gases, at least those of spallogenic origin, do not readily diffuse in meteoritic metal, and to the extent that they do diffuse they are not fractionated (1). It has also been shown that the metal phase of gas-rich meteorites contains less-fractionated gases than the silicates in the same meteorites (2). Since combustion experiments carried out on iron meteorites for the purpose of releasing nitrogen (3) have shown that spallogenic noble gases (and, in the case of Washington County (4), trapped noble gases) are released in a quantitative and apparently unfractionated way from metal when it is oxidized, it seemed to us that combustion of metal from gas-rich meteorites might be a useable technique for extracting solar wind noble gases unaltered and uncontaminated by other noble gas components -- a situation not previously attained for Kr and Xe except in the exterior of a lunar ilmenite separate (5). By limiting the available oxygen, the depth of combustion can be controlled. This minimizes the release of spallogenic gases, the only other noble gas component expected in the metal.

~~The optimum experiment would involve combustion of a pure metal separate.~~ In order to avoid chemical, and even harsh physical, treatment of ~~our~~ ^{the} sample, which might have affected the surfaces of metal grains, ~~we devised a means of analyzing the metal in the presence of residual silicate not removed by gentle crushing and magnetic separation.~~ ~~Our preliminary results, given in the table below, were obtained by taking advantage of the differing properties of metal and silicates with regard to diffusion.~~ We established on a silicate separate that after an initial 300°C pyrolysis step, a further 300°C pyrolysis produced amounts of He and Ne lower by a factor of 7 than the initial step. We also found that a 250°C pyrolysis following a 300°C pyrolysis yielded a reduction of two orders of magnitude in gas release from the silicates. It is assumed, although not yet proven, that at 300°C essentially no gas is lost from the metal in the absence of oxygen. We therefore carried out two experiments on a grain-size separate of metal from the gas-rich Weston H-group chondrite, involving an initial 300°C pyrolysis followed by either a 250°C combustion or a 300°C combustion in a limited amount of oxygen. In the case of the 300°C combustion, a repeat pyrolysis at 300°C established the contribution of the silicates to the combustion step. In the case of the 250°C combustion, a 250°C pyrolysis followed the 300°C pyrolysis and preceded the combustion, establishing the silicate "blank" contribution. Because the 250°C combustion appeared to be incomplete, it was repeated with more oxygen, and then followed by another pyrolysis step. All heating steps were 45 minutes long. The presence of radiogenic ⁴⁰Ar in the silicates, which was released along with solar gases, provided us with a check on the constancy of the diffusive release from the silicates between combustion steps and the pyrolytic steps which served as blanks.

The results of the combustion step at 250°C indicate that the amounts of O₂ used may have been insufficient to completely oxidize the solar-wind-containing zone in the metal. One gets the impression that the gases have been implanted

at depths corresponding to their energies and have not been completely mixed since that time, since it appears that one can etch inward and preferentially remove first the He and then the Ne. The high $^{20}\text{Ne}/^{22}\text{Ne}$ ratio would in this view be due to the oxidation front not penetrating to the maximum implantation depth of ^{22}Ne . The low amounts of Ar obtained in the 250°C steps (not shown in the table, because the "blank" correction made them very imprecise) support this view, since the Ar would be more deeply sited. The main point of this experiment, however, is demonstrated by the results of the 300°C experiment. The O_2 to metal ratio was higher, so oxidation would have penetrated more deeply, helped by the higher temperature as well. The measured He:Ne:Ar ratios, as well as the $^4\text{He}/^3\text{He}$ and, to a slightly lesser extent, the $^{20}\text{Ne}/^{22}\text{Ne}$ ratios, are all in excellent agreement with the results for the metal phase of Pantar (2), and with the present-day solar wind Ne:Ar and $^{20}\text{Ne}/^{22}\text{Ne}$ ratios obtained by the Apollo Solar Wind Composition experiment (6). This in spite of the fact that the correction for the silicate contribution in the 300°C combustion step amounted to about 30% of the total gases released.

The results of this experiment suggest that, with some modifications in the choice of pyrolysis and combustion temperatures and in the amount of O_2 used, it should be possible, by oxidizing the surfaces of metal grains from gas-rich meteorites, to obtain data on solar wind that has not been fractionated by diffusive loss. Measurements on Kr and Xe should be attainable simply by scaling up the amount of metal used, and there should be very little chance of mixing of other Kr and Xe components into the metal-sited solar wind gases because of the low contents of noble gases in metals in general. The one potential problem that might occur is the possible presence of combustible phases, other than the metal, which may be noble gas carriers. Obviously, the best solution would be a clean metal separate, but the above technique provides a feasible experimental approach even in the absence of a pure separate.

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	T (°C)	ΔO_2 (mtorr-ℓ)	$\frac{^4\text{He}}{^{20}\text{Ne}}$	$\frac{^{20}\text{Ne}}{^{36}\text{Ar}}$	$\frac{^4\text{He}}{^3\text{He}}$	$\frac{^{20}\text{Ne}}{^{22}\text{Ne}}$	$\frac{^{21}\text{Ne}}{^{22}\text{Ne}}$	$\frac{^{36}\text{Ar}}{^{38}\text{Ar}}$
*Weston #1 (23.8 mg)	250	9.2	1040 ±70	-	2340 ± 20	15.4 ±.3	0.0360 ±.0008	-
	250	4.8	808 ±54	-	2260 ± 25	14.6 ±.2	0.0353 ±.0008	-
	250	-	714 ±61	-	2270 ± 60	15.1 ±.5	0.0347 ±.0013	-
*Weston #2 (15.2 mg)	300	11.4	794 ±53	47.2 ± 4.0	2310 ± 20	13.4 ±.1	0.0353 ±.0003	5.43 ±.07
Pantar Metal (2)	-	-	745	-	2200	13.8	0.0383	-
SWC (6)	-	-	570 ±80	45. ±11.	2350 ±120	13.7 ±.3	0.0323 ±.0042	-

* grain diameter range: $63\mu < d \leq 1000\mu$

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N86-28022

PARTICLE TRACK MEASUREMENTS IN LUNAR REGOLITH BRECCIAS. George E. Blanford, University of Houston - Clear Lake, Houston, TX 77058.

The Regolith Breccia Initiative and the recent publication of the Regolith Breccia Workbook (1) make it a particularly appropriate time to review the published track data on lunar regolith breccias. These data are summarized in Table 1.

Particle track measurements have been reported for only 25 (5%) of the regolith breccias in the collection; they have been reported for 16 breccias (30%) of the reference suite (1). No measurements were found in published papers for any Apollo 17 breccias. Unfortunately, many of the track measurements in lunar breccias were made before it was realized what parameters were relevant to measure. The earliest papers emphasized surface exposure ages. Later, when it was understood that regolith breccias retained tracks from the epoch prior to compaction, reports of high track density grains were emphasized. It is not clear from most papers that track density frequency distributions are determined from a random sampling of grains; the earliest papers seem to have immature track density frequency distributions and later papers seem to have mature track density frequency distributions (cf. 10046).

The most frequently reported measurement for the 25 breccias in Table 1 is the maximum surface exposure age of the compacted rock (48% of the published breccia measurements). Information on the nature of the precompaction regolith is given for 9 rocks (36%) and on the nature of the compaction event for 6 rocks (24%).

Realizing that the breccias listed in Table 1 are not likely to be a random sampling of the collection, some general features are nevertheless worth noting. Most of the breccias appear to have simple post-compaction surface exposure histories (89 %). From the few track density frequency distributions (7) that are available and inferring from the relatively low exposure ages of these rocks (75% $\leq 10^6$ a), it appears that most of these breccias are very amenable to studies which separate the contemporary surface exposure age from information about the precompaction regolith. Therefore, it is regrettable that regolith breccias seem to have been systematically avoided for the later Apollo missions because of their supposedly complex irradiation histories. If the number of immature-submature precompaction soils (6 out of 10 of the breccias for which appropriate data are available) is representative of many regolith breccias, then we can infer that many regolith breccias may sample the deeper, less reworked materials in the lunar soil and compliment the samples available from the returned cores. The relative immaturity of the precompaction soil is an observation which is consistent with models of regolith breccia formation by subsurface impact compaction. The fact that regolith breccias are more friable than crystalline rocks and metamorphosed breccias

TRACK MEASUREMENTS IN BRECCIAS

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Table 1
Particle Track Measurements in Lunar Regolith Breccias

ORIGINALLY REPORTED DATA						
SAMPLE	EXPOSURE HISTORY†	MAXIMUM SURFACE EXPOSURE AGE (a)	METHOD	MATERIAL	MAXIMUM SURFACE EXPOSURE AGE** (a)	COMMENTS
10046*	SS		SP	Glass? (h)	1.3×10^6	Immature based on the number of low track density grains (g) Mature track density frequency distribution (k)
10059						Mature track density frequency distribution (k)
12034*			SP	? (j)	2.1×10^7	
14047*	SS	3.4×10^6 (s)	SP	?	1.0×10^6	
14049*	SS					Mature track density frequency distribution (k)
14055*	SS	5×10^4 (s)	SP	?	8×10^4	
14267						Submature track density frequency distribution (k)
14301*	SS	3.4×10^5 (s)	SP	Plagioclase	2.4×10^5	Immature track density frequency distribution (s,x)
		8×10^6 (d)	SD	Plagioclase equivalent?	1.8×10^7	Submature based on % track rich grains (v)
14307*	SS	5×10^6 (y)	SP	Pyroxene	1.4×10^5	
14315*	MS			Plagioclase		Shock altered, immature based on % track rich grains (v)
14318*	MS			Plagioclase		Shock altered, immature based on % track rich grains (v)
15015*	SS	13 (z)	G	Pyroxene, Glass	35 ± 30	
15086*	SS			Plagioclase		> 90% track rich grains, mature track density frequency distribution (r,x)
15205*	SS	8×10^4 (t)	G	Pyroxene, Glass	$2.2 \pm 1.8 \times 10^5$	Calculated using originally published correction factors
15265*	SS	1×10^6 (c)	ST	?	5×10^5	
15418?						High shock metamorphism (v) Metamorphosed or immature? (x)
15426	SS	5×10^5 (o)	SP	Glass	1.4×10^5	Immature track density frequency distribution (o)
		1.5×10^7 (c)	SD	?	4.3×10^7	

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15459		$1.0-3.0 \times 10^7$ (e)	SD	Corrected to Plagioclase	††	
15505*	SS	6×10^5 (n)	SP	Pyroxene	3.5×10^5	
60255*	SS			Plagioclase		Track annealing characteristics used to comment on thermal history (x)
61175*	SS	2×10^7 (p)	SP	Plagioclase	4.4×10^7	
66055?						Metamorphosed or immature? (x)
67015						Metamorphosed or immature? (x)
67016		1.5×10^7 (u)	G (w)	Plagioclase	5×10^5	Mistakenly reported in (u) as 67015
68815	SS		G	Plagioclase	$2.4 \pm 0.3 \times 10^6$	Used to obtain a track production curve by (1,aa,bb)

* Reference suite (1).

† SS - single stage, i.e., only one surface is heavily cratered.

MS - multi-stage, i.e., heavy cratering on more than one surface.

†† SP - A single point measurement using one of three versions of the track production curve determined from the surveyor glass filter (cf. a,i,m,q).

G - A measured track gradient with depth was determined and used with one of the surveyor references given above.

SD, ST - Subdecimeter and Suntan ages - using models and differential energy spectrum reported by (b). Depths are arbitrarily taken at 1 mm for ST ages and 3 cm for SD ages (d).

** Recalculated using the track production profile of (f). Cf. (gc) for a review of the measured lunar track production profiles. Rock densities were taken to be 2.8 g/cm^3 . It was assumed that tracks were counted on surfaces perpendicular to the rock surface with an infinite flat surface geometry; these two conditions insure maximum ages. No corrections were made for etchable range or etching efficiencies with respect to plagioclase in which the track production curve was measured. For the SP and G methods the minimum track density model was used [cf. e.g. (h)]. ST and SD ages assume depths of 1 mm and 3 cm, respectively.

†† Insufficient published data to recalculate an age.

††† Published data were incomplete, but a reasonable back calculation appeared to be possible.

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TRACK MEASUREMENTS IN BRECCIAS

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is consistent with the relatively young exposure ages for regolith breccias.

It is clear from this review that lunar regolith breccias have not been systematically studied using particle track techniques. As has been done, the contemporary maximum surface exposure age can be measured for these rocks. These measurements should be statistically related to the contemporary meteoroid flux. The best method for determining this age is to measure a minimum track density gradient 0.5 - 2 cm below the exposed surface in order to minimize the problem of surface erosion and yet have fairly high track densities. A gradient measurement was made for only 4 of the rocks studied. Volumes deeper than 3 - 5 cm from the exposed rock surface, for simply exposed rocks, will have a sufficiently low number of contemporary tracks that the precompaction regolith can be studied. By measuring minimum track densities, track density frequency distributions, and the percent of track rich grains, as has been done for lunar cores, one can determine whether or not lunar regolith breccias retain ancient, "frozen" lunar stratigraphy and one can compare that "fine" structure to present day lunar cores and to meteoritic regolith breccias. Such studies have not been done on regolith breccias. Potentially even more valuable information can be gained from comparisons of contemporary correlation studies with correlations in the ancient regolith. For example, it is known that track rich grain abundances correlate with ferromagnetic resonance intensities (2) and to solar wind gases (3). The ratios of solar wind ^{36}Ar to the abundance of track rich grains (4) or the median track density (5) are being used to compare the ancient solar wind flux to the present flux in lunar soil samples. Comparisons of the ratios of track rich grain abundances with ferromagnetic resonance intensities in contemporary soils to similar ratios in the ancient regolith should give us some insight on the relative strengths of modern to ancient meteoroid fluxes. Information gained from comparisons of contemporary and ancient conditions on the Moon can then be more useful for comparing these same kinds of measurements in lunar samples with those in meteorites.

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SCR and GCR Exposure Ages of Plagioclase Grains from Lunar Soil 61501.
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EU 259631

Goal and Approach: The concentrations of solar wind implanted ^{36}Ar in mineral grains extracted from lunar soils show that they were exposed to the solar wind on the lunar surface for an integrated time of 10^4 to 10^5 years (1,2). Down to a depth of 2-3 cm spallogenic Ne and Ar are produced more efficiently by the solar cosmic radiation (SCR) than by the galactic cosmic radiation (GCR)(3). At a depth larger than about 10 cm SCR produced spallogenic gases amount to less than 0.1% of those produced by the GCR. ^{38}Ar GCR exposure ages of plagioclase grains from lunar soils computed with nominal mean production rates range from 50 to 500 Ma (1,4). Because the knowledge of the residence time of a soil sample at different depth could serve as an experimental test of models for the regolith dynamics (e.g. 5), it is of interest to resolve the spallogenic products into the SCR and GCR produced fraction. Several such attempts, predominantly based on the isotopic composition of Ne, have been reported (6-11).

Difficulties: In principle it is possible to resolve the spallogenic nuclides detected in a given sample into the SCR and GCR produced portions because of the differing energy and target element dependencies of the production rates of the various spallogenic nuclides. Therefore, the decomposition requires the knowledge of the chemical composition of the sample as well as its shielding history. The latter constitutes the first difficulty encountered, because this information is intrinsically not available and has to be modeled appropriately.

The second difficulty arises in the precise determination of the concentrations and isotopic ratios of the spallogenic elements in lunar materials because of the presence of implanted gases. In constituents of lunar soils, the concentrations of implanted gases generally exceed those of the spallogenic gases by several orders of magnitude. Even in samples from lunar rocks very fine soil particles blown into the pore space of the rock on the first exposure to atmospheric pressure may lead to difficulties in the determination of the spallogenic component. Thus, in both cases, the implanted gases must be experimentally depleted to such a degree that the isotopic ratios and concentrations of the spallogenic gases can be determined without impairing corrections or assumptions.

The third difficulty concerns the experimental separation of the two types of spallogenic gases. Because the grains -or samples- investigated are small in comparison to the attenuation length of even the SCR interaction, attempts for experimental separation of the two spallogenic components, such as stepped heating or etching, are bound to fail.

Our Study: From the bulk soil 61501 we prepared plagioclase separates of 8 grain size ranges. The depletion of the implanted gases was achieved by etching aliquot samples of 4 grain sizes to various degrees. (nominal thickness of the removed layers: 1 - 40 μm)(12). The experimental results pertinent to the present discussion are as follows: The spallogenic ^{38}Ar concentration is $(68 \pm 9) \times 10^{-8}$ ccSTP/g. The concentration of spallogenic Ne is, as in most plagioclases from lunar soils, affected by diffusive losses and of no use here. The ^{36}Ar of solar wind origin amounts to $(2030 \pm 100) \times 10^{-8}$ ccSTP/g in the 150 - 200 μm size fraction and shows that these grains were exposed to the solar wind for at least 10'000 years. The $^{21}\text{Ne}/^{22}\text{Ne}$ ratio of the spallogenic Ne is 0.75 ± 0.01 and in very good agreement with

the value of this ratio in a plagioclase separate from rock 76535 (13). This rock has had a simple exposure history and its plagioclases have a chemical composition quite similar to those studied here. In addition to the noble gases, we also investigated the heavy particle tracks in an aliquot of the 150 - 200 μm plagioclase separate and found 92% of the grains to contain more than 10^8 tracks/ cm^2 (14,15). According to (2,15) this corresponds to a mean track density of $(5 \pm 1) \times 10^8$ tracks/ cm^2 .

To evaluate these results with respect to possible shielding histories, we modeled two exposure scenarios:

1. In addition to the 10'000 years of solar wind exposure, the sample resides for the rest of its effective exposure time at only one constant depth.
2. The sample is excavated -or buried- with a constant rate of 1mm/Ma (5). This is equivalent to the assumption of a random up-and-down motion with equal residence time at each depth interval.

Taking into account the chemical composition of our plagioclases, we computed the Ne and Ar production rates as a function of shielding depth (3) for SCR and GCR exposures. Furthermore, the track densities at the center of 150 - 200 μm plagioclase grains were computed (16). The comparison of the experimental results and the computed values show that for both scenarios appropriate depth-time histories can be found:

- * An exposure for some 400 Ma at a depth of about 10 cm (or $20\text{g}/\text{cm}^2$) in the first scenario or an excavation from a depth of 43 cm (taking 430 Ma) in the second scenario produce the observed spallogenic ^{38}Ar concentration, the inferred track density as well as spallogenic Ne with a $^{21}\text{Ne}/^{22}\text{Ne}$ ratio close to the measured one.
- * The first exposure history leads to a SCR contribution to the total of the spallogenic gases of less than 1 % and even in the second scenario merely 4 and 8 % of the spallogenic Ne and Ar, respectively, are SCR produced.

Conclusions: The exploration of the exposure history of the plagioclase separates from the soil 61501 do not contradict the model for the regolith dynamics (5) but also fail to prove it. The evidence for a comparatively short (<5 %) SCR exposure is compelling. During this stage, all solar wind gases, a large fraction of the tracks but very little spallogenic Ne and Ar were accumulated. This is in sharp contrast to the conclusions reached for other soils (8-11). Spallogenic Ne with a $^{21}\text{Ne}/^{22}\text{Ne}$ ratio lower than commonly found in meteorites is not necessary an indication for a significant SCR exposure; it may be the result of chemical differences.

The exercise reported here demonstrated to us: To unravel the depth-time history of samples exposed to SCR and GCR, real high accuracy of the experimental and theoretical input data about the spallogenic and solar gases, the sample chemistry as well as the track data are of crucial importance.

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THE COMPOSITION OF LUNAR NOBLE GASES TRAPPED 2.5 AE AND
3.6 AE AGO.

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The times when the soils 74001 and 73261 were exposed on the lunar surface were determined using the ^{235}U - ^{136}Xe dating method. ~~As these soils were excavated by the Shorty-Grater impact only 17 m.y. ago, they most probably acquired their surface correlated trapped gases during their pre-exposure period 3.6 AE and 2.5 AE ago, respectively.~~ The isotopic composition of the trapped noble gases in these two soils is compared with that of the surface correlated noble gases in the "young" soils 12001 and in the present day solar wind.

A strong time dependency is observed for the ratio $^{40}\text{Ar}/^{36}\text{Ar}$, which decreases from a value of 10.8 for soil 74001 to 0.37 for 12001. Less pronounced decreases are observed for the ratios $^4\text{He}/^3\text{He}$, $^{22}\text{Ne}/^{20}\text{Ne}$, $^{38}\text{Ar}/^{36}\text{Ar}$, $^{80}\text{Kr}/^{86}\text{Kr}$, $^{82}\text{Kr}/^{86}\text{Kr}$, $^{134}\text{Xe}/^{132}\text{Xe}$, and $^{136}\text{Xe}/^{132}\text{Xe}$ ratios.

The surface correlated trapped gases are a mixture of implanted solar wind particles and re trapped lunar atmospheric gases. We interpret the observed changes ^{as a result of decreasing outgassing of radiogenic ^{40}Ar and perhaps ^4He and of fissiogenic Xe from the lunar crust.} The old soils probably also contain surface correlated ^{80}Kr and ^{82}Kr produced by secondary cosmic ray neutron capture of adsorbed or re-trapped bromine. To some extent the isotopic composition of the trapped gases in old lunar soil may also have been altered due to diffusion loss from material of low retentivity. When substantiated by further data points, the ratios which show a time dependency, e.g. the $^{40}\text{Ar}/^{36}\text{Ar}$ ratio, may be a useful indicator of the implantation time of trapped gases or of the time of compaction of regolith breccias.

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THE DATING OF PRE-EXPOSURE TIMES OF LUNAR ROCKS AND SOILS.

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Xenon produced by fission of uranium, thorium and plutonium has repeatedly been observed in lunar rocks and soils. In two basaltic rocks, 12053 and 14310, and in two soils, 74001 and 74261, we also found ¹³⁶Xe ^{was found} originating from fission of ²³⁵U induced by neutrons which are due to the interactions of cosmic-ray particles with lunar matter. Two facts lead to this conclusion: (i) fission Xe is present in excess of that expected for the U, Th and Pu concentrations and for the gas retention age of the samples, and (ii) the ¹³⁴Xe/¹³⁶Xe ratio of excess fission Xe is close to 1.25 as expected for neutron induced fission of ²³⁵U. Information on the duration of the exposure to cosmic rays was obtained from the ⁸¹Kr-Kr systematics whereas the effective shielding conditions were derived from the depth sensitive cosmogenic ratio ¹³¹Xe/¹²⁶Xe. For the four samples the exposure to cosmic rays in the lunar regolith is described by a two-stage exposure model. The history of the four samples was derived in terms of duration and shielding depth of the two stages.

In the two rocks 12053 and 14310 a large proportion of ¹³⁶Xe and ¹³⁴Xe is fission produced and more than half of the fission Xe is neutron induced. For the two rocks we calculated pre-exposure times of 3.1 AE and 2.5 AE ago, respectively. This method for dating the time of a pre-exposure in the lunar regolith is of particular interest for soils which might have acquired trapped gases from the solar wind or the lunar atmosphere during the pre-exposure period. The two soils 74001 and 74261 which show an excess of neutron fission yield pre-exposure times of 3.6 AE and 2.5 AE, respectively, the latter value being preliminary.

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RELEASE OF NOBLE GASES AND NITROGEN FROM GRAIN-SURFACE SITES IN LUNAR ILMENITE BY CLOSED-SYSTEM OXIDATION. Urs Frick, Richard H. Becker and R. O. Pepin, School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455.

M2165962

Noble gases and nitrogen were extracted from a 100-150 μ ilmenite separate from lunar soil 71501 by closed-system stepped heating in ~ 10 torr O_2 at 300 $^\circ$, 400 $^\circ$, 500 $^\circ$, 600 $^\circ$ and 630 $^\circ$ C, followed by stepped pyrolysis at ten temperatures between 680 $^\circ$ and $\sim 1500^\circ$ C. The five oxidation steps together liberated $\sim 65\%$ of the total 4He , 45% of the ^{20}Ne , 23% of the ^{14}N and ^{36}Ar , 12% of the ^{84}Kr and 8% of the ^{132}Xe in the sample; $^{20}Ne/^{36}Ar$ and $^{20}Ne/^{22}Ne$ ratios agree with the Solar Wind Composition experiment(1), and $^{84}Kr/^{36}Ar$ and $^{132}Xe/^{36}Ar$ are within $\sim 10\%$ of Cameron's(2) estimates for the sun and solar wind. The remaining gases, released above 630 $^\circ$ C by pyrolysis, are strongly fractionated with respect to the SWC-Cameron solar wind elemental composition. This imprints a fractionation pattern on the total gas composition in the sample which agrees with that measured in other lunar ilmenites.

These data point to the presence of an ilmenite grain-surface reservoir containing nearly unfractionated solar wind noble gases (with, however, some diffusive depletion of the lightest species: $^4He/^{20}Ne$ in the summed 300-630 $^\circ$ C fractions is $\sim 60\%$ of the SWC ratio, and $^4He/^{3He}$ is somewhat higher than the SWC value). The gas release mechanism up to 630 $^\circ$ C presumably involves structural transformations induced by oxidation of $FeTiO_3$ to $Fe_2O_3 + TiO_2$ (3). We have no independent information on how deeply this oxidative alteration may have penetrated into grain surfaces. However, the more or less solar ratio of Xe to lighter gases suggests oxidation to at least the base of the implantation zone for solar wind Xe ions ($\sim 500\text{\AA}$?).

The $^{14}N/^{36}Ar$ ratio in gases released from the surface reservoir is more than an order of magnitude higher than Cameron's solar estimate. Neither N contamination nor an indigenous (non-solar-wind) N component can easily account for this excess. It could, however, be consistent with the presence of fractionated noble gases sited in grain interiors (below the surface reservoir). According to dynamic models developed by Maurette and co-workers at Orsay(4-6), lunar grains in this size range experience multiple exposures to the solar wind during an episode of residence near the top of the regolith. Each exposure populates the grain-surface reservoir with solar wind ions. But for most (>99%) of its residence lifetime in a surface stratum, between direct exposures to the wind at the surface, the average grain is shallowly buried in the thermally active upper regolith. During this time diffusive migration of noble gases both inward and outward from their implantation sites could generate the fractionated gases in grain interiors and depopulate the surface reservoir prior to the next exposure to the solar wind. The N excess in the surface reservoir is presumably then due to a much smaller diffusion coefficient (because of chemical bonding to the medium), leading to incomplete N depletion of the reservoir and superposition of multiple doses of solar wind N in grain surfaces.

Large concentrations of fractionated noble gases in grain interiors, their virtual absence in the relatively unfractionated surface gas reservoir, and the high N/noble gas ratio all imply that most of the solar wind noble gases initially implanted in grain surfaces are eventually lost by diffusion. Loss limits can be estimated by considering the following two scenarios. (in which we assume that Cameron's solar Xe/Ar and N/Xe estimates are approximately right for the solar wind):

(1) About 3/4 of the total N in 71501 ilmenite is released in the >630 $^\circ$ C pyrolysis steps, and thus appears to be sited in grain interiors ($d \geq 500\text{\AA}$). If this N ($\delta^{15}N = -10 \pm 10\%$, $N = 4.3\text{ppm}$) is indigenous, then only the N in the surface reservoir is from solar wind. The ratio of this surface-sited

N to total Xe in the sample is within $\sim 15\%$ of Cameron's solar N/Xe ratio. If this is not coincidental, it implies that neither N nor Xe has been lost to any significant extent (unless both species are implanted to the same depth and diffuse in the same way). Loss of a lighter noble gas such as Ar is then fixed by the depletion of the measured Ar/Xe ratio below solar. In the ilmenite, Ar/Xe is 29% of solar; therefore 71% of the Ar has been lost. This is a minimum loss factor for Ar in any scenario, since it depends only on total Xe and the solar Ar/Xe ratio.

The obvious difficulty with this model is its failure to account for the fact that only a small fraction of the total Xe (with \sim solar Xe/Ar ratio) is removed by the surface oxidation. If Xe has not been lost by outward diffusion, it should also not have diffused inward, and most of it would still be in grain-surface sites and susceptible to release by oxidation (with Xe/Ar $> 4 \times$ solar). If oxidation did not penetrate to the base of the solar wind implantation zone, then of course much of the Xe in the zone would have been retained. But then one requires a double assumption: that Cameron's Xe/Ar estimate is too low, at least for the solar wind, by a factor of 4 or more; and that the Xe/Ar ratio in the gas that was released coincidentally mimics this incorrect value.

(2) If all the N in the ilmenite is of solar wind origin, the fact that $3/4$ of it lies below the $\geq 500\text{\AA}$ deep surface reservoir implies that it has been redistributed by diffusion. Fick's Law calculations indicate that $\sim 80\%$ of the initial inventory of N implanted in grain surfaces would have been lost during such a diffusive redistribution. N/Xe in the fractionated (grain interior) gases is $3.9 \times$ solar. Therefore Xe must have been depleted by a factor $\sim 3.9 \times 5 \approx 20$. A similar result is obtained by applying Fick's Law directly to Xe diffusion. Since Xe/Ar in the surface reservoir is approximately solar, very little of the fractionated component can reside there as a "contaminant": only $\sim 2\%$ of its Xe would have a $\sim 30\%$ effect on the surface reservoir Xe/Ar ratio. Most of the fractionated Xe must thus lie below the depth of oxidation. The constraint that $\geq 98\%$ of the Xe in the fractionated component must reside below the $\geq 500\text{\AA}$ oxidation depth requires very extensive diffusive redistribution from its original implantation sites into this configuration. In the process, $\geq 90\%$ of the initial Xe inventory, and $\geq 97\%$ of the Ar, are lost.

We conclude, therefore, that $\sim 70 - 97\%$ or more of the Ar implanted in 71501 ilmenite grains by the solar wind has diffusively escaped, and that losses on the high end of this range are most probable.

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BOUNDARY CONDITIONS ON THE EARLY SUN FROM ANCIENT COSMOGENIC NEON IN METEORITES. C. M. Hohenberg, M. W. Caffee and T. D. Swindle, McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130 USA; and J. N. Goswami, Physical Research Laboratory, Navarangpura, Ahmedabad 380 009, India.

Isotopic analysis of neon from individual grains of the meteorites Murchison (CM) and Kapoeta (howardite) shows large enrichments of cosmogenic neon in grains with solar flare tracks. The quantity of this component is incompatible with GCR or SCR irradiation under present conditions and is attributed to irradiation by energetic flares from an early active sun [1]. Handpicked grains from each meteorite were grouped according to the presence or absence of solar flare heavy ion tracks, and these four samples (an irradiated and an unirradiated group from each meteorite) were analyzed with an ion-counting noble gas mass spectrometer.

While galactic cosmic ray exposure ages for the unirradiated grains yield the nominal values reported for the recent, well-documented, exposure histories of the meteorites, the irradiated grains contain large excesses of cosmogenic Ne-21. If these excesses were attributed to GCR irradiations, minimum pre-compaction exposure ages of 28 m.y. and 56 m.y. are obtained for Murchison and Kapoeta, respectively, irradiated as individuals in free space (4 π geometry and at the peak of the production curve). The required GCR exposure times for regolith settings are several hundred million years, far longer than the 1 m.y. or so allowed by most models for the irradiation of gas-rich meteorites [2]. The other possible source of the cosmogenic neon is irradiation by solar cosmic rays. However, irradiation under present conditions would again require 100 m.y. of exposure at 3 A.U. [1].

This seems to leave two possibilities: 1) models for the irradiation of gas-rich meteorites are wrong, and exposure periods (presumably in regoliths) lasted up to two orders of magnitude longer than predicted; or 2) gas-rich meteorites were irradiated by an early sun with a flux of energetic protons up to two orders of magnitude higher than the present-day flux. If the latter is the case, further constraints can be set on the early solar system. First, the postulated active early sun would seem to have had a harder energy spectrum than at present, since the isotopic composition of the cosmogenic neon is closer to that produced by galactic cosmic rays than that produced by present-day, lower-energy solar cosmic rays [1]. Second, there is an apparent lack of solar wind neon (an upper limit of less than 20 years exposure, compared to 100 years or more predicted by most models), perhaps indicating shielding by nebula gas or thin coatings on the grains themselves. One difficulty is, of course, the fact that Kapoeta is a differentiated meteorite, with evidence of formative activity or impact metamorphism as late as 3.6 b.y. [3, 4]. Thus, if these grains were irradiated by an active early sun, they must not have been seriously affected by these later processes.

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THE REALITY OF THE SECULAR CHANGE IN SOLAR WIND NITROGEN ISOTOPES

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Evidence concerning the isotopic composition of N in the early solar system currently seems to favor a picture of isotopic inhomogeneity [1] rather than of a unique primordial composition modified by local processes. Certainly the range of $^{15}\text{N}/^{14}\text{N}$ ratios found in meteorites points to the existence of more than one nucleogenetic N component, though mass-dependent modification of them is not ruled out. A two-component model has also been advanced to explain the isotopic variation observed for N in the lunar regolith [1,2]. Here we address the observational evidence which can be used to discriminate between such a model and one invoking a secular change in the composition of the solar wind [3].

The two components hypothesised to account for the lunar data are: solar wind N (SWN) with a constant $\delta^{15}\text{N}$ value of about +120% relative to terrestrial air; and a hypothetical light "planetary" N (LPN) component with $\delta^{15}\text{N} < -230\%$, the lowest value yet measured in ancient lunar breccias [4]. LPN is inferred to have outgassed from the lunar interior, its proportion relative to SWN decreasing with time as its internal reservoir became exhausted.

Three tests of this model have been considered so far, starting with a search for LPN surviving in lunar igneous rocks [2]. Results so far are negative; lunar rocks give $\delta^{15}\text{N}$ values close to 0 [5]. The other two tests depend on the fact that, because ^{14}N is so much more abundant than ^{15}N , a variation in LPN-content sufficient to produce the observed change in $\delta^{15}\text{N}$ also has significant effect on total N content. In the lunar regolith, such an effect would be manifested by a systematic perturbation in the relationship between N content and duration of exposure of samples to the solar wind. Such a perturbation may be revealed in two ways, both of which utilise a couple of independent measures of surface exposure: content of solar wind-implanted ^{36}Ar ; and the fraction of indigenous Fe^{2+} reduced to Fe^0 by solar wind-implanted H and impact-induced melting [6].

In one approach, the relative contributions due to SWN and LPN may be calculated for each sample analysed. The calculated SWN contents correlate less well with each surface exposure parameter than do total N contents [1].

The other approach is the inverse calculation; LPN should show up as a systematic deviation from the trend-line between total N content and duration of surface exposure, and the deviation should correlate with departures of $\delta^{15}\text{N}$ from the SWN value. In fact, no deviation and no correlation may be seen [7].

The results of these tests may not eliminate the two-component model for regolith N but they seriously weaken it. The alternate view, involving a secular change in SWN composition [3], has its problems [1] but continues to survive by default [8].

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DISTRIBUTION OF SOLAR WIND IMPLANTED NOBLE GASES IN LUNAR SAMPLES

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The distribution of solar wind implanted noble gases in lunar samples depends on implantation energy, fluence, diffusion, radiation damage and erosion. It is known that at least the lighter rare gases are fractionated after implantation, but the redistribution processes, which mainly drive the losses, are not well understood. Some information about this one can get by looking at the concentration profiles of solar wind implanted ^4He measured by the Gas Ion Probe (1) in single lunar grains (> 100 microns).

The observed profiles have been divided in three groups (2). THESE GROUPS ARE ILLUSTRATED AND BRIEFLY DISCUSSED.

I) Surface profiles, characterized by the position of maximum ^4He concentration within the direct implantation range (figure 1).

II) Deep profiles, characterized by the position of maximum ^4He concentration below the direct implantation range and in comparison to type I a much broader gas distribution (figure 2).

III) Double humped profiles, characterized by two maxima, one at the very surface and a second one between 300 and 600 Å. This type of profile is mineral specific and up to now only found in olivines (figure 3).

The expected mean range of implanted solar wind He in lunar samples is typically 200 Å (3). However, near this value The maximum ^4He concentration is only found in some few ilmenites. All the other recorded profiles seem to be more or less changed by secondary processes mainly by diffusion under the special condition of severe radiation damage. Erosion by sputtering is believed to be a less important process in changing the ^4He implantation profile and is not taken into consideration.

In a simple model the evolution of a rare gas implantation profile under lunar conditions was described (4). According to this model it is shown on single ilmenite grains that the fractionation of the residual noble gases increases, when the position of maximum ^4He concentration is found nearer toward the surface. By using this correlation one can separate ilmenites with ^4He profiles corresponding to a low degree of fractionation. Such classes of ilmenites selected from different samples may be suitable to look for variation in composition and energy of present and past solar wind.

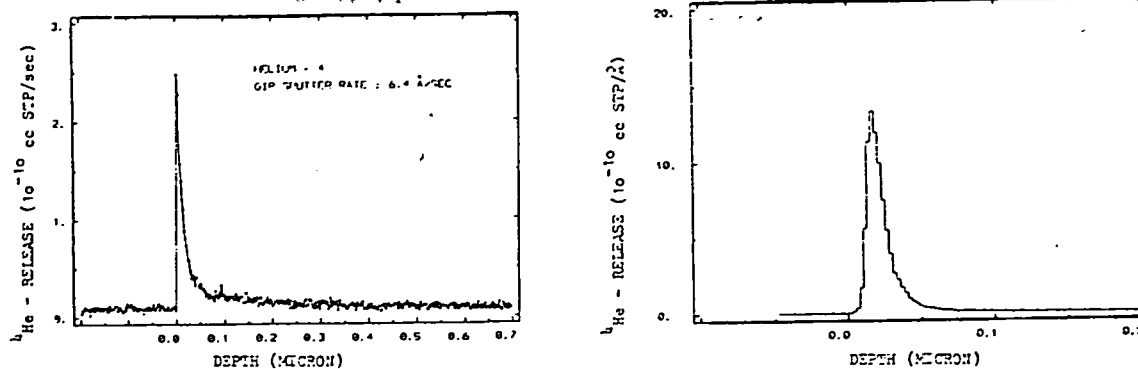


Fig. 1) Surface profiles with maximum ^4He concentration within the direct implantation range of the solar wind. The example on the left shows an He profile in a pyroxene with maximum concentration immediately at the surface, on the right in an ilmenite He has the highest concentration at 170 \AA .

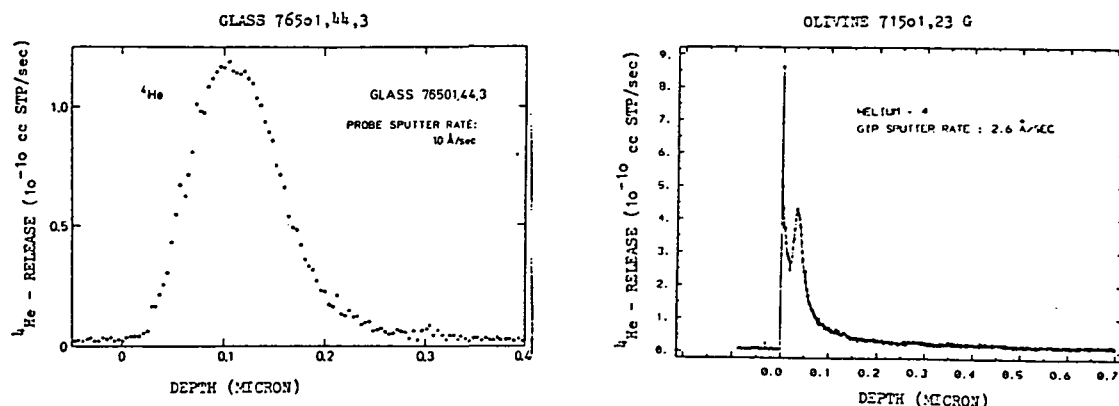


Fig. 2) Deep profile with maximum He concentration at a depth of 1100 \AA .

Fig. 3) Double humped profile with two He maxima one at the very surface and a second one at 320 \AA .

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THE NEED FOR ISOTOPIC DATA ON REFRACTORY ELEMENTS IN THE SOLAR WIND

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The sun accounts for the bulk of material in the solar system. Information on the isotopic composition of elements in the solar wind is therefore essential for an understanding of the contribution made by each nucleogenetic component that has been identified in meteorites. Recent work in our group suggests that isotopic data on the solar wind may also help us understand the physical process that is concentrating light elements at the solar surface.

THIS HYPOTHESIS IS BRIEFLY DISCUSSED

The present data base on isotopic abundances of elements in the solar wind consists mostly of volatile elements that could be easily resolved from indigenous lunar material. The possibility of alterations in the isotopic composition of these elements by mass dependent fractionation may limit their utility in resolving nucleogenetic from physical effects.

Recently we noted (Manuel and Hwaung, 1983) that the isotopic composition of noble gases in the solar wind can be understood as a mixture of the two major planetary noble gas components (Sabu and Manuel, 1980): He, Ne and Ar in the sun are type-X, Xe is type-Y, and solar Kr is a mix of these two planetary noble gas components. Resolution of solar-wind-implemented gases into these two components required correction for a velocity-selection, mass fractionation process that spans several orders of magnitude across the mass range (3-136 amu) represented by the stable isotopes of the five noble gases.

Previously, isotopic fractionation in noble gases has generally been assigned to a planetary process, e.g., diffusive gas loss. Planetary fractionation fails to explain several features in the elemental and isotopic abundance patterns of planetary and solar-wind-implemented noble gases. The relationship between planetary and solar-wind-implemented gases instead suggests a solar fractionation process that enriches lighter nuclei at the sun's surface.

Such a process is not entirely unexpected. Abundances of elements at the solar surface display a steep decrease in abundance over the mass range spanned by the noble gas isotopes. Chapman and Cowling (1952) note that lighter nuclei will tend to diffuse towards the cooler region of an ionized gas. Further, they point out that, "This must happen in the sun and the stars, where thermal diffusion will assist pressure diffusion in concentrating the heavier nuclei towards the hot central regions."

Refractory and volatile elements would behave alike under the conditions of solar fractionation. Prolonged exposure of foils at 1AU from the sun would be a relatively inexpensive way to collect the quantity of solar-wind-implemented refractory elements needed to test this hypothesis.

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PETROGRAPHIC SURVEY OF LUNAR REGOLITH BRECCIAS

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Regolith breccias from the moon and from parent bodies of some meteorites may provide us with samples of ancient regoliths which have been frozen in time. If these rocks were essentially closed at some earlier time and we can determine that time, then these rocks provide a record of conditions in the solar system at that point in time. The breccias may record the composition and relative abundance of solar wind species. They may record the flux and composition of the meteoroid complex. They may record outgassing conditions and volcanic activity of their parent body. For the moon, the record of lunar surface interactions frozen in regolith breccias may extend backward in time far beyond the oldest core sample and may fill in the large time gap extending from the time at which the material in the lunar cores was buried to the time of the last volcanic activity as recorded in the basalts. Even if the closure time of regolith breccias cannot be determined with certainty, the probability that these regolith breccias contain samples of regoliths closed off at some time other than the present is reason enough to investigate them and to determine if a record of a solar system environment different than the present-day one can be deciphered.

Lunar regolith breccias are probably better understood than meteorite regolith breccias mainly because the geologic setting is relatively well known. However, among the lunar samples, regolith breccias have been the least studied sample type and the data on them are sparse compared to other rock types and particularly to the lunar soils and cores. We have therefore started a survey of regolith breccias in the Apollo collection concentrating initially on Apollo 15 and 16. We have surveyed all available thin sections for 32 regolith breccias from Apollo 15 and 19 breccias from Apollo 16. These are most of the returned regolith breccias larger than 1 cm from these two missions. For comparison we have also investigated several fragmental matrix breccias which do not strictly qualify as regolith breccias. We are using the definition of Stoffler et al. (1979). The criteria for classification as a regolith breccia is the presence of identifiable soil components such as glass spheres or agglutinates.

Following our usage in McKay and Wentworth (1983) we are classifying the breccias according to their intergranular porosity. In addition we note the fracture porosity, and the relative abundance of agglutinates and spheres. Of the 32 examined Apollo 15 breccias, 16 are porous to subporous and 16 are compact to subcompact. Where available, we have analyzed more than 1 section of each breccia; for some as many as 4 sections have been studied. The porosity characteristics of the breccia is similar from section to section of the same rock although some slight variation exists; the porosity variations among breccias is clearly not an artifact of thin section preparation. Examples of porous regolith breccias include 15086, 15265, 61175, and 63507. Examples of compact regolith breccias

include 15205, 15295, and 60019.

~~We have noted~~ several petrographic trends. ^{Wentworth NOTED} Identifiable regolith material decreases with decreasing intergranular porosity while fracture porosity increases. For the most compact breccias, regolith components are normally rare and consist mostly of small glass spheres. This correlation between porosity and identifiable soil components may reflect the maturity of the soil from which the breccia was made or it may result from some aspect of the breccia making process which destroys regolith components or makes them difficult to identify. Even the most mature of the porous regolith breccias do not appear to have as many identifiable soil components (agglutinates, glass spheres) as typical soil samples.

This relative lack of maturity of regolith breccias may reflect their generally earlier formation age and the maturity of the regolith at that earlier time. Alternatively, it may reflect the relative immaturity of that part of the regolith from which the breccias were made, deeper zones for example. Other mechanisms which may influence the maturity of regolith breccias include mixing of regolith and comminuted bedrock and a change in the meteorite flux distribution over geologic time. Additional data may help to choose among these possible explanations. One implication of these observations is that meteorite regolith material of greater maturity than that observed in collected meteorites may exist but may not be preserved in meteorite regolith breccias. Clearly, an understanding of the petrology of lunar regolith breccias will contribute to our understanding of meteorite regolith breccias and may lead to a more complete record of solar system history.

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SOLAR FLARE NEON AND SOLAR COSMIC RAY FLUXES
IN THE PAST USING GAS-RICH METEORITES
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We have earlier ^{well} developed (Venkatesan et al., 1980 and Nautiyal et al., 1981) methods to deduce the composition of solar flare neon and to determine the solar cosmic ray proton fluxes in the past using etched lunar samples and at present, we are extending these techniques ^{ade. ex. re. no. to} to gas-rich meteorites.

We have determined noble gas elemental and isotopic composition in gas-rich meteorites, Weston, Elm creek, Leighton and Pantar by step-wise gas-release procedures. By combining these results with the existing data on Fayetteville and Kapoeta (Black, 1972 and Manuel, 1969) we find that Ne data points at low temperatures ($<6000-8000^{\circ}\text{C}$) fall along the tie-line joining the contemporary SW-Ne end point ($20/22 = 13.6$) with the SF-Ne end point ($20/22 = 11.7 \pm 0.3$). Further we find a similar behaviour in case of selected lunar samples. The Ne observed in low temperature fractions seems to be varying mixtures of SW and SF components. Our results suggest that the composition of implanted SF-Ne in gas-rich meteorites is close to 11.7 ± 0.3 which is consistent with the values deduced earlier using etched lunar mineral separates (Nautiyal et al. 1981; Wieler et al., 1982).

By considering high temperature ($>6000-8000^{\circ}\text{C}$) Ne data points for Pantar, Fayetteville and other gas-rich meteorites and by applying the three component Ne-decomposition methods, we could resolve the SCR and GCR produced spallation Ne components from the trapped SF-Ne. Using appropriate SCR and GCR production rates, in the case of Pantar, for example, we estimate a GCR exposure age of 2 m.y. for Pantar-Dark while Pantar-Light yielded a GCR age of ~ 3 m.y. However the SCR exposure age of Pantar-Dark is two orders of magnitude higher than the average surface exposure ages of lunar soils. The possibility of higher proton fluxes in the past is discussed.

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LUNAR NITROGEN - SECULAR VARIATION or MIXING?

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The two current models to explain the nearly 40% variation of the lunar nitrogen isotopic composition (from $-210^{\circ}/\infty$ (1) to $+170^{\circ}/\infty$ (recorded by us from soil 73221) are (i) secular variation of solar wind nitrogen (2,3) and (ii) a two component mixing model having a constant, heavy solar wind ($+120^{\circ}/\infty$) admixed with varying amounts of indigenous light lunar N - LLN (4). Both models need to explain the step pyrolysis extraction profile (Fig. 1). The secular variation model proposes that the low temperature ($600^{\circ}\text{C} - 900^{\circ}\text{C}$) release is modern day solar wind implanted into grain surfaces, the $900^{\circ}\text{C} - 1100^{\circ}\text{C}$ release is from grain surfaces which were once exposed to the ancient solar wind but which are now trapped inside agglutinates, and the $>1100^{\circ}\text{C}$ release as spallogenic N produced by cosmic rays. The mixing model ascribes the components to solar wind, indigenous lunar- and spallogenic N respectively. An extension of either interpretation is that the light N seen in lunar breccias or deep drill cores represent conditions when more ^{14}N was available to the lunar surface.

If the ancient solar wind was isotopically light then, according to the secular variation model, evidence for this ought to be found within agglutinate grains. This is not so (5), but (6) - Fig. 2 - and (7) have both shown that it can be found within mineral grains. Alternately, if light N is indigenous it ought to be resolved by stepped extraction of lunar rock material, this is not so from both our work (Fig. 3) and (8). Geiss and Bochsler (4) postulated that, because of the heavy, spallogenic component, LLN would be difficult to resolve by this method. To suggest that a two component extraction would be more difficult to resolve than the three component mixing seen in lunar soils seems unreasonable, as Fig. 1 shows a small, light component resolved from between two heavy components.

Work on acid resistant residues from the Allende and Murchison meteorites (9) has revealed the existence of an ultra light N (ULN) component (possibly the same as the one proposed by (4)). Pyrolysis of Allende (9,10) and residue BB (Fig. 4) shows that ULN is evolved around 900°C , with a minimum isotopic value (in CC) of $-326^{\circ}/\infty$ (9). As both volatile and trace element studies (11,12) show that 1-2% of carbonaceous chondrite material has survived impact and is now admixed with the lunar soil, it seems reasonable to suggest that some of this material could be similar to the acid- and heat-resistant phase that is found in Allende.

An extra-lunar but non-solar wind source for LLN has several advantages, thus ULN - (i) could survive impact whereas other C- and N-rich phases would volatilise, (ii) need only be added in very small quantities ($<10\text{ppm}$), (iii) could have been more abundant in the past as more meteorites abounded, (iv) may help explain the apparent "enrichment" of N compared to rare gases, (v) does not need a mechanism which only changes solar corona source for a single element. Since, in Allende, ULN is associated with C that is isotopically normal ($\delta^{13}\text{C}$ ca $-38^{\circ}/\infty$) C isotope values need not exhibit (5) the same large isotopic variations seen for N. For the above model to work successfully the C/N ratio of the meteoritic phase which survived impact and was deposited in the lunar regolith would

need to be low.

Further detailed study of separates from lunar regolith breccias is needed before an explanation of the light N found within them can be put forward.

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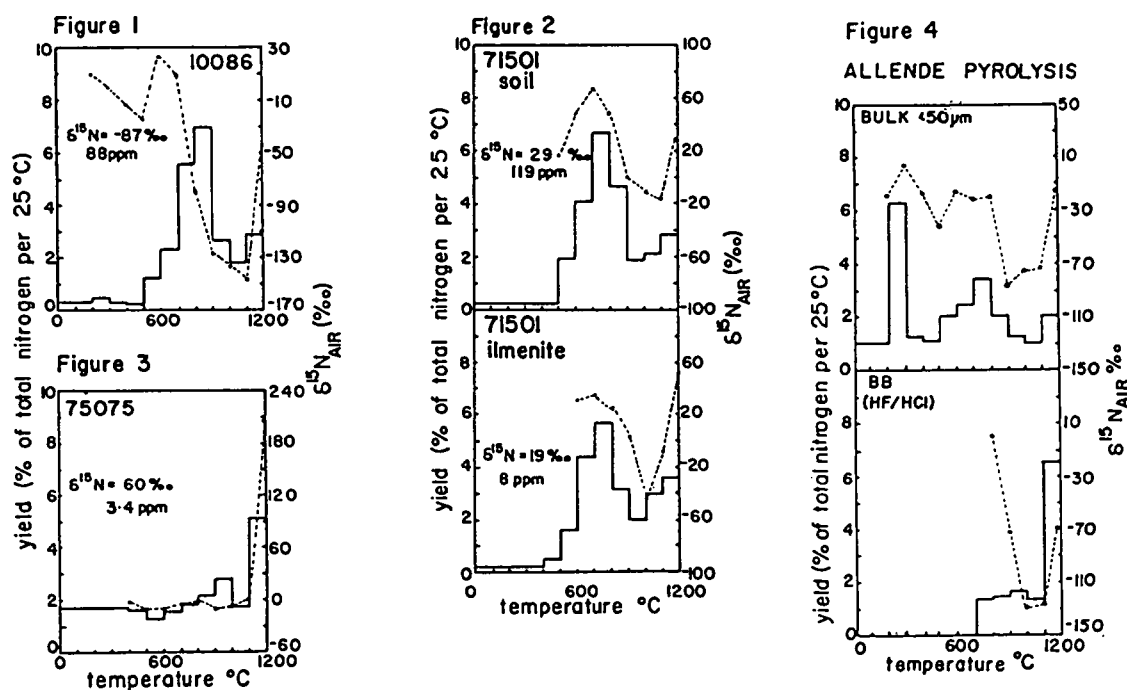


Figure 1. Pyrolysis of breccia pebble from soil 10086.

Figure 2. Pyrolysis of bulk soil and ilmenite fraction from sample 71501.

Ilmenite sample donated by P. Signer and R. Wieler, ETH Zurich.

Figure 3. Pyrolysis of lunar basalt 75075.

Data for these three figures from 600 to 1200°C inclusive.

Figure 4. Pyrolysis of Allende and Allende BB. Bulk data are:-

Allende <50µm $\delta^{15}\text{N} = -36\text{‰}$, 17.2 ppm

Allende BB $\delta^{15}\text{N} = -74\text{‰}$, 2317 ppm. This data from (9).

9179 Nitrogen and Noble Gases in the 71501 Bulk Soil and Ilmenite as Records of the Solar Wind Exposure: Which is correct? P. Signer, H. Baur, Ph. Etique and R. Wieler. ETH Zürich, Sonneggstrasse 5, 8092 Zürich, Switzerland.

The N determination in mg sized mineral separates from lunar soils by static mass spectrometry (1,2) is an experimental break-through likely to contribute to the deciphering of the records left in the mineral grains by the exposure to the solar wind. In this discussion we focus on some comparisons of the results of N (2) and noble gas analyses of the 71501 bulk soil and an ilmenite separate thereof. Conclusions from noble gas data obtained on mineral separates from some 20 soils (3,4,5) are summarized in a companion paper (6) and will be also considered here.

The N/36-Ar ratios in the bulk soil and 100-150 μm sized ilmenites are 720 and 520, respectively. Both values are much above the value of 26 (7) for the solar abundance and indicate that Ar is severely depleted not only in the mature bulk soil but also in the ilmenite. Apparently, lunar soil grains and even ilmenite retain only about 5 % of the total impinging solar wind Ar. This conclusion is, of course, based on the assumptions of a solar wind origin of the N and quantitative retention.

The N concentration in the ilmenite grains allows to compute the minimum duration of their exposure to the solar wind. This minimum exposure is the sum of all individual exposure episodes, assuming that the grains are always exposed to acquire solar wind on their full geometric cross section. To compute the mean acquisition rates of solar wind species on the lunar surface, one has to account for the shielding of the moon from the solar wind by the geomagnetic tail, the day-night cycle and the angle of incidence. On the lunar equator and at zero longitude the mean acquisition rates amount to 9.3 % of the free-space flux of the solar wind at 1 AU (8). With these rates, a free-space solar wind particle flux of 2.7×10^8 particles/cm², sec, a H/N ratio of 11'500 (7) and the measured N concentration, a minimum SW exposure time of the ilmenite of 110'000 years is computed. Similarly, one derives a minimum SW exposure time from the 36-Ar concentration of 5400 years by using a H/36-Ar ratio of 298'000 (7). The real surface exposure time is certainly longer than the minimum exposure time, may be about a factor of 10, because the grains are bound to be partly buried during their exposure episodes. Thus, the real SW exposure of the ilmenite grains deduced from the N data is likely to be on the order of 1 Ma. Such a long residence time of grains on the surface of the regolith leads to the following conflicts:

- * The track density at the center of 150-200 μm plagioclase grains acquired during the 1 Ma of real surface exposure is about 3×10^9 tracks/cm² (9). During the residence of the grains in the uppermost cm of the regolith, the track density is further increased. Yet, the actually measured mean track density is only 6.7×10^8 tracks/cm² (5). For this argument, similar evolutions of the ilmenite and plagioclase grains are presumed.

- * The extrapolation of the destruction probabilities for rocks in the 10 g to 10 kg mass range (10) to the masses of the grains studied here (about 3 μg) yield a 99 % destruction probability by a primary impacts of about 20'000 years. Thus, the real exposure times of mineral grains as deduced from the N concentration appear much longer than the mean life times of the grains.

- * Based on Ar and He analyses of single grains it was concluded that the Ar concentrations in plagioclase grains are not determined by saturation (4). Furthermore, the erosion rate of such grains appears to be less than 2 $\mu\text{m}/\text{Ma}$ (4). If the erosion rate is governed by ion sputtering, the much larger SW

dose implied by the N concentrations may cause larger erosion. This is not only conflicting with the above conclusion but also leads to the release of implanted N to the lunar atmosphere. Freed N is then recycled to the lunar surface by the Gold-Manka-Michel process as proposed for 40-Ar. Because of the low trapping yield ($\leq 5\%$, (11)) the recycling leads inevitably to a net loss of N. Therefore, the SW dose necessary to account for the retained N is further increased and one is led into a vicious circle.

The N concentrations not only in the 100-150 μm ilmenite grains but also in the bulk soil are uncomfortably high, especially if the present-day solar wind flux is used to deduce SW exposure times. To account for the N concentrations in bulk soils an enhanced flux of SW nitrogen in past times has been postulated (12,13). The new data (2) of N in the 71501 bulk soil and ilmenite accentuate this problem in two respects:

- * A regolith having a thickness of 3 m, a density of 2 g/cm³ and the same N and Ar concentrations as the soil 71501 requires 44 Ga to accumulate its N from the solar wind with a present-day flux. Therefore, the mean N flux seen by this soil must have been at least 10 times higher than the present-day N flux in the solar wind.

- * The N concentration of the ilmenites requires that they were exposed while the N flux was still high. Because the 38-Ar GCR exposure age of the 71501 ilmenites is about 100 Ma (3) and because we contend that mineral grains from most surface soils have acquired their solar species essentially in the last 10-100 Ma, the high mean flux should have lasted until about 10 Ma ago.

We now turn to the discussion of the isotopic composition of N, Ne and Ar. From the studies of olivine/pyroxene and ilmenite separates from some 10 soils we conclude that the 20-Ne/22-Ne ratio of solar wind Ne retained in Ne retentive minerals remained constant within $\pm 2\%$ during the last 1 to 3 Ga (5). Thus, a possible temporal change of this ratio in the solar wind (14) is less than 2%. N appears thus, besides Ar, to be the only element where substantial changes ($\sim 30\%$) of the isotopic composition with time are observed (c.f.12). Ar in mineral separates shows variations of the 40-Ar/36-Ar ratio, possibly also time correlated, in excess of 1000% (5).

Summary and Conclusions. The newly reported N concentrations in the soil 71501 and its ilmenites (1,2) have not only aggravated the problem of the disparity of the N/Ar ratios in lunar soils and the assumed solar ratio but also the question of the high fluxes of N in the solar wind. It appears that the mean flux of N was more than 10 times larger than it is since 10 Ma. Otherwise, N in lunar soils must have other sources besides the solar wind. Indigeneous lunar N has recently been considered as one alternative source (2,15). The remarkable fact that the gases with the largest isotopic variations in lunar soils are also comparatively abundant in the terrestrial atmosphere may indicate still other sources.

Ref: (1) Frick & Pepin (1983), pers. comm.; (2) Norris et al. (1983), 46th Ann. Meeting Met. Soc., Mainz; (3) Signer et al. (1977), PLSC 8th, 3657; (4) Wieler et al. (1981), PLPSC 11th, 1369; (5) Wieler et al. (1983), PLPSC 13th, A713; (6) Wieler et al. (1983), this volume; (7) Cameron (1982), in: Essays in Nucl. Astroph., Cambr. Univ. Press; (8) Etique (1982), PhD Thesis, ETH Zurich; (9) Blanford et al. (1975), PLSC 6th, 3557; (10) Horz et al. (1975), PLSC 6th, 3495; (11) Geiss (1973), Proc. 13th Int. Cosm. Ray Conf., 3375; (12) Clayton & Thiemens (1980), Proc. Conf. Anc. Sun, 463; (13) Kerridge (1980), Proc. Conf. Anc. Sun, 475; (14) Pepin (1980), Proc. Conf. Anc. Sun, 411; (15) Geiss & Bochsler (1982), GCA 46, 529; (16) Yang et al. (1982), GCA, 46, 841; (17) Knab et al. (1983), in prep. Work supported by the Swiss National Foundation.

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E.H.?

Studies of light noble gases in mineral grains from lunar soils; a status report. R. Wieler, Ph. Etique, and P. Signer, ETH Zurich, Sonneggstrasse 5, 8092 Zurich, Switzerland.

Among the lunar soil constituents, monomineralic grains deserve special attention. Our group has concentrated since several years on noble gas studies of carefully prepared mineral separates from lunar bulk soils. Here, we summarize the major results and conclusions of these investigations in the context of both, the regolith evolution and the history of the solar corpuscular radiation. With regard to the most abundant noble gas component in regolith samples - the solar gases - the mineral grains have mainly two properties giving these particles among all soil constituents the best characteristics as sensors for solar gases, despite the fact, that the noble gas concentrations in a mineral separate are 10 - 60 times lower than those in a bulk sample of the same grain size. The first of these properties is the mineral dependent retentivity of the light gases He and Ne, the second property concerns the relatively short time during which a mineral grain acquires its solar gases. In the following, these two points are discussed:

Retentivity of solar He and Ne: The table shows the ranges of He/Ar and Ne/Ar in various constituents (refs 1 & 2) and the solar values (3):

	ilmenite	oliv./pyro.	plagioclase (highl.)	solar
4-He/36-Ar	5000 - 11000	300 - 600	40 - 80	20000
20-Ne/36-Ar	15 - 30	6 - 16	1 - 2	26

In sharp contrast to the He and Ne amounts, the solar Ar concentrations in all mineral separates in a given grain size range from the same bulk soil always agree to within $\pm 25\%$, as was shown for about 20 soils (1,2). It was concluded that the implanted solar wind Ar (SW Ar) is retained to better than 70% in all mineral grains of the lunar regolith, and that diffusional losses and not sputtering cause the low abundances of solar He and Ne. The good retentivity of all lunar soil constituents for SW Ar seems to disagree with the Ar/N ratios in bulk soils and mineral separates. These ratios are about 20-10 times lower than the assumed solar value (cf. 4-6). This important problem is discussed further in a companion abstract (7).

Lifetime of minerals: Primary particles are constantly admixed to the regolith by erosion of rocks and pebbles. Conversely, these particles are also constantly broken up and/or incorporated into secondary particles like microbreccias and agglutinates. In contrast to the latter particles, minerals therefore acquire their solar gases during a relatively short time interval. We estimate the mean lifetime of a population of clean mineral grains (150 - 200 μm) in the reworking zone of the regolith to be on the order of 50 Ma. (8). This estimate is based on the noble gas and track record in plagioclases of North Ray Crater soil 67601. The material of this soil was added to the regolith only about 50Ma. ago. Despite this, the minerals from 67601 have among the highest observed solar Ar concentrations as well as among the highest track densities of all surface soils studied (2). Nevertheless, the plagioclase grains in this or in any other soil are not saturated with solar wind Ar, as our analyses of He and Ar concentrations in nearly 100 single grains each from a gas poor and a gas rich mineral population showed. Evidently, for mineral grains in the 150 - 200 μm grain size range, residence times of more than 50Ma. near the regolith surface lead to destruction of these grains. The results of Monte Carlo computations for the regolith

turnover rate (9) can be used to estimate that the time between the first and the last surface exposure of a population of clean minerals in many cases is not longer than 100Ma. Of interest in this context is the observation that the 38-Ar GCR exposure age and the SW Ar concentrations of "dirty" plagioclase grains of soil 61501 in a relatively large grain size (200 - 300 μ m) are both nearly a factor of two higher than the respective values of clean grains in the same size range of the same soil. At least for this soil, the dirty mineral population must have had a longer evolutionary history than the clean minerals (10).

The solar corpuscular radiation in the past and today: A large number of separates of olivine, pyroxene, and ilmenite - minerals fairly retentive for SW Ne - was investigated (8). Comparison of the Ne data of surface soils on the one hand, and drill core samples and soil breccias on the other hand revealed that the 20-Ne/22-Ne ratio of SW Ne has not changed drastically with time. A possible secular increase of this ratio over the past 2 - 3 Ga. is smaller than 2%.

Studies of aliquots of a plagioclase separate etched to various depths revealed a Ne component with a 20-Ne/22-Ne ratio of about 11.3 in the first several ten microns below the grain surface (11). This component is most plausibly interpreted as solar flare implanted Ne (SF Ne). Due to the strong depletion of SW Ne in plagioclases by diffusion, the SF Ne can amount to as much as 20 - 50% of the total solar Ne in this mineral. The 20-Ne/22-Ne ratio of this flare component differs from the value of 7.6 ± 2 measured in a few contemporary flares by satellite borne instruments (12, 13).

The SF Ne detectable in mineral grains of the lunar regolith opens up new possibilities - besides the SW gases and the SF tracks - to trace back the history of the solar activity over the last few billion years. For this purpose, we need data on etched mineral separates from early and recently exposed samples.

So far, no etching experiments on early irradiated samples have been made. At present, the SF component in plagioclase must therefore be calculated from the 20-Ne/22-Ne ratio of the solar component (superposition of SW Ne and SF Ne), by assuming a constant composition of spallogenic Ne in each sample. A low $(20\text{-Ne}/22\text{-Ne})_{\text{sol}}$ is then indicative for a relatively high SF Ne contribution. This approach is justified because the $(20\text{-Ne}/22\text{-Ne})_{\text{sol}}$ correlates inversely with the 20-Ne/36-Ar ratio. This is expected, because the retained SF Ne is likely to have a larger Ne/Ar ratio than the retained SW Ne in plagioclases. The $(20\text{-Ne}/22\text{-Ne})_{\text{sol}}$ also correlates with the Mean Track Density/36-Ar ratio, which is another and independent flare/wind flux measure. The drill core and soil breccia samples investigated have on average a two times higher MTD/36-Ar ratio than surface soils. This indication for an about two times higher flare/wind flux ratio 1 - 3 Ga. ago is supported by the inverse correlation of $(20\text{-Ne}/22\text{-Ne})_{\text{sol}}$ in plagioclases and the 40-Ar/36-Ar ratio in mafic minerals of the same soils. The latter ratio is thereby taken as a rough indicator of the time when a sample was exposed at the regolith surface.

Ref: (1) Signer et al. (1977), PLSC. 8th, 3657; (2) Wieler et al. (1981), LPSC. 11th, 1369; (3) Cameron (1982), in: Essays in Nuclear Astrophysics, Cambr. Univ. Press; (4) Clayton & Thiemens (1980), Ancient Sun, 463; (5) Norris et al. (1983), 46th Ann. Meeting Met. Soc., Mainz; (6) Frick and Pepin (1983) in prep.; (7) Signer et al. (1983), this volume; (8) Wieler et al. (1983), LPSC. 13th, A713; (9) Borg et al. (1976), EPSL 29, 161; (10) Etique (1982), PhD Thesis, ETH Zurich; (11) Etique et al. (1983), to be publ. in GCA; (12) Dietrich & Simpson (1979), Astrophys. J., 231, L91; (13) Mewaldt et al. (1979), Astrophys. J., 231, L97.

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